Leveraging Commercial Software Defined Radio for Low Cost Deep Space Testing

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***Abstract* – In a typical space mission development life cycle, there is a stage where the spacecraft needs to test against the ground station for interface compatibility to ensure that the spacecraft will be properly tracked after launch. This testing normally requires the spacecraft team to bring their flight equipment to the ground station facility. While recognizing that testing with actual flight or engineering module is the most preferred option because of maximum fidelity, there are occasion when the use of actual flight hardware is a logistically challenge because of spacecraft development. Having another test tool that can emulate the spacecraft signal – by recording the signal transmitted by the spacecraft and regenerate an RF signal for ground system testing - would be very useful. It is even more an attractive option if such spacecraft emulator is inexpensive and highly portable.**

In this paper, we describe a low-cost, light-weight recorder/playback assembly (RPA) that supports deep space missions testing. The equipment leverages on commercially available software defined radios (SDR) and public-domain software. The RPA has been used to support two missions. One effort is to validate that the Uchinoura 34-m tracking station of the Japanese Aerospace Exploration Agency (JAXA) would be able to track the upcoming NASA Exploration Mission 1 (EM-1) spacecraft, scheduled for launch in 2019. The second effort is to help with the testing and certification of the 21-m antenna ground station at the Morehead State University (MSU) in Kentucky, United States, prior to the time when the Lunar IceCube spacecraft is ready for actual compatibility testing. The RPA also enables students/staff training of the new ground station, using the RPA signal as test input into the system. This low-cost test signal allows the MSU team to save money on not having to develop a full-scale self-generated telemetry test signal source.

Keywords - SDR; RF Test Capability; Uchinoura; Morehead State University Ground Station.

I. INTRODUCTION

In a typical life cycle of deep space mission development, there is a period prior to launch where the flight communications system needs to be tested for interface compatibility against the ground station that provides later spacecraft tracking after launch. This testing normally requires the spacecraft team to bring their radio to the ground station test facility. These tests exercise various modes of spacecraft operation, e.g., different data rates, coding schemes, signal levels, to ensure that the signal can be processed by the ground station. While this is a good practice to ensure the compatibility between flight and ground system, there are occasions when such a test poses some logistic problem to the flight team, e.g., their equipment may be tied up with other development effort. Having a test instrument that can serve as a substitute for flight equipment – a tool that can record the signal transmitted by spacecraft and recreate an RF signal for injection into the ground station - would provide much flexibility. The benefits are even greater if such a spacecraft emulator is very affordable and highly portable, as in this case, because it reduces the financial burden on the project and simplify the shipping logistics when conducting tests.

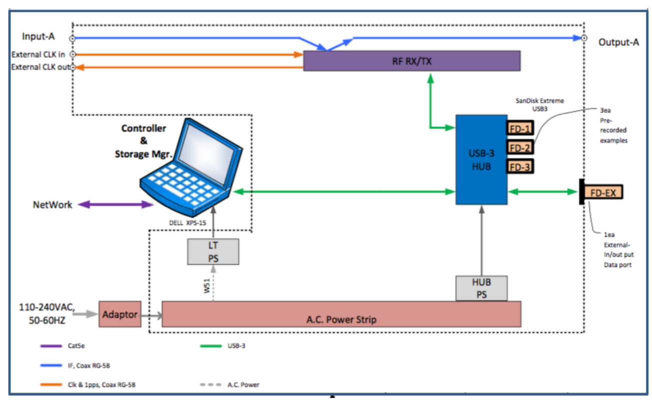

Figure 1. Components of the Recorder Playback Assembly

Section II of this paper discuss the design and capability of the Recorder/Playback Assembly (RPA). The benefits of the equipment are captured in Section III. Some possible improvements to the equipment operations, from our perspective, are offered in Section IV. Support to the EM-1 mission testing is described in Section V, followed by a discussion on the Morehead State University in Section VI.

II. DESIGN ARCHITECTURE

The Recorder/Playback Assembly comprises of three key components: (1) a laptop computer with fast input/output (via USB3 connections) to enable data transfer from the transceiver to a disk storage, (2) a high capacity data storage (~3 Terabytes), and (3) a commercial SDR RF transceiver. The computer provides the graphical user interface for user to control the signal generation. It configures and controls the setting of the transceiver. In the recording mode, the computer transfers digitized samples from the transceiver to the disk storage. In the playback mode, it reverses the digital sample flow, from the disk storage to the transceiver. In addition, the laptop also generates an FFT spectrum of the recorded or playback signal, based on the digitized samples. The second component – the disk storage - archives the samples. Both the computer and disk storage use the high speed USB3 interface for data transfer.

The most crucial element of the RPA is the RF transceiver [1]. The particular unit we used in the RPA can sample an RF signal input up to a rate of 20 Msps, I/Q sampling. To have the recorded data possibly used by other SDRs (e.g., for future upgrade), we chose to have the digitized samples written in the standard 32-bit format. This prompts a high I/O rate (80 MB/s) and a large data storage capacity. Our particular chosen SDR supports an input/output RF frequency range of 1 MHz - 6 GHz. This allows the signal recording or playback directly at the S-band (~2.3 GHz) that the ground station expects to be receiving from EM-1 spacecraft. For the Morehead State University testing with Lunar IceCube, since the spacecraft RF transmitted signal will be at X-band (8.4 GHz), our test signal is set at intermediate frequency of ~300 MHz and injected to the receiver after the RF/IF Downconverter.

The SDR transceiver can run with an internal clock or be synchronized to an external 10 MHz reference. Since the SDR expects a Low Voltage Transistor Transistor Logic (LVTTL) input level for the frequency reference, we needed to build an adapter to convert a typical sinusoidal reference (+13 dBm) to that of LVTTL. This adapter essentially is a resistor-capacitor-diode network to level shift and clamp the signal level to the 0-volt minimum and the 3.3-volt maximum required for LVTTL compatibility. The use of an external frequency reference from a highly stable clock, such as those produced by a Hydrogen maser at both ground stations of JAXA and MSU, produces a significantly more stable signal, which is critically important to our test objectives. Performance of the signal stability with and without the external reference is discussed in later section VI.

The control software of the transceiver is leveraged on some public-domain software available from the gnu library, which is another benefit for using commercial SDR. We developed two modes of operation: one for recording, the other for playback. Figure 2 shows a sample of the graphical control interface for data recording. By specifying the local oscillator frequency, typically a few MHz off from the actual carrier frequency, we can position the signal to be sampled away from the dc component. Figure 3 shows a similar control window for playback where selection of the data file and output frequency can be made, along with other detailed parameters such as the setting of RF, IF and baseband gain. In both record and play back modes, a Fast Fourier Transform (FFT) spectrum is provided, as seen in Figure 4, to aid with signal monitoring.

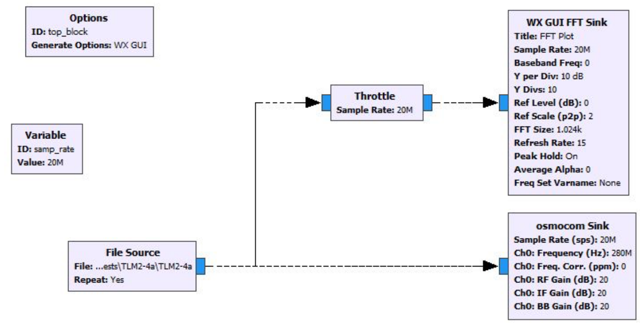

Figure 2. Control Interface for Recording

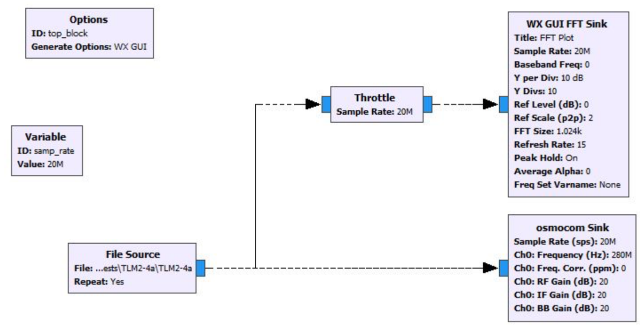

Figure 3. Control Interface for Playback

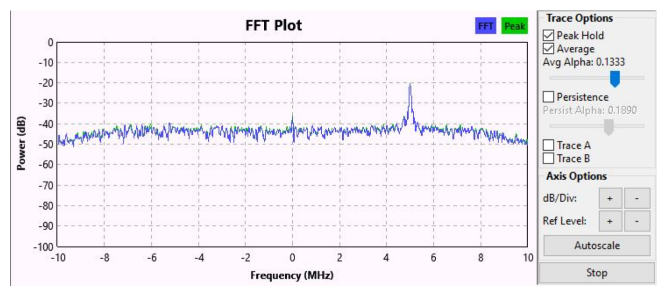

Figure 4. Spectral monitor of recorded/playback signal

III. BENEFITS

From our experience, below are some key benefits of the RPA.

(1) *Low Cost* - One big benefit of this test capability is its low cost. The hardware cost, purchased in 2016, is in the order of $2K. It took about one month of effort to put together the control software and testing. In application where one need to replicate a test signal source available elsewhere, this low-cost recorder/playback capability is a very attractive option.

(2) *Portability* - Another feature we highly value is the equipment portability. The whole assembly weighs less than 7 lbs., making it very easy to hand carry when travelling to distant test site.

(3) *Upgradability* - Since the SDRs are commercially products and supported by a large user community who also provide some standard interfaces and functionality, as more powerful new products become available, the system could easily be upgraded without much effort.

(4) *Flexibility* - The wide range frequency supported by the transceiver provides much flexibility with testing. It allows us to inject the test signal directly into the front-end of ground system at S-band frequency (the same signal path traveled by spacecraft signal during operational phase), or some intermediate frequency in mid-stream of the system. The ease of changing carrier frequency makes it easy to simulate different spacecraft signals that we tried to test.

(5) *Efficiency* - The RPA can generate signal with data repeat option. That means it can continually regenerate the signal with only a small set of recorded data; thus, reduces the need for a large data storage or long recording session.

IV. FUTURE IMPROVEMENTS

Although the RPA sufficiently supports our testing needs, there are certain features that we would consider pursuing to improve its operation:

(1) *Gain setting* - The gnu library allows for the gain setting of three stages: baseband, IF and RF. With the mid-level setting, we were able to capture and regenerate the signal with nominal power and with good quality (i.e., without distortion). But we did not have enough time to fully explore all combination of gain setting for optimal setting.

(2) *Recorded data trimming* – Some of our recorded data files started earlier than the actual data segment of interest. With the current operation, the entire data file is replayed, resulted in some wait time until the interested segment is reached. It would be more efficient to have a tool to trim the data file to just those segments of interest.

(3) *Higher frequency* – As more commercial products become available with greater capability, while remain cost competitive, we would consider upgrade the SDR to those at go beyond X-band (8.4 GHz) to further enhance testing capability at the MSU and future X-band missions.

V. EM-1 MISSION SUPPORT

One of the objectives of the RPA development is to provide test support to the Exploration Mission 1, currently scheduled to be launched in late 2019 [2]. The EM-1 spacecraft will be on a three-week trajectory that takes it to the Moon, stays in the parking orbit for a few days, and then returns to Earth. EM-1 is intended to demonstrate the operation of new spacecraft system, along with the new Space Launch System, prior to the crewed Exploration Mission 2 currently scheduled in 2022-2023. In support of future crewed mission, especially for the Earth return segment, precise navigation and spacecraft orbit determination are important. For EM-1, most of the tracking during the mission three-week operations will be provided by the NASA Deep Space Network; however, in the interest of getting supplement tracking data during the critical phase of the mission, e.g., Earth return, the mission also likes to have additional 3-way Doppler data from the JAXA antenna.

The focus of JAXA support is mainly on tracking EM-1carrier signal and providing 3-way Doppler data to the mission navigation. 3-way refers to a mode where the DSN would be providing an uplink to the spacecraft and JAXA antenna will be tracking the spacecraft downlink, in concurrent with DSN tracking. No telemetry processing is expected from Uchinoura station.

Usually, we could leverage a spacecraft currently in flight that has the same signal format to test the ground system compatibility. However, EM-1 signal format is different from other lunar missions currently in operation, such as the Lunar Reconnaissance Orbiter (LRO). EM-1 telemetry data is directly modulated onto the carrier, which is at 5 MHz offset from the downconverted local oscillator, as shown in Figure 4. In contrast, the LRO signal would be modulated on a subcarrier, prior to carrier modulation. To ensure that Uchinoura system can track the EM-1 signal, it was decided that a replica of EM-1 signal – being recorded and played back by the RPA – should be used to check out the flight/ground interface. The main objective is to demonstrate that the receiver at the Uchinoura station can track the carrier in the presence of telemetry modulation and provide good, stable Doppler data.

A preliminary test was recently conducted using the RPA to characterize the Doppler data tracked by Uchinoura station [3]. The RPA previously recorded the EM-1 RF test signal during its compatibility testing with the Deep Space Network. The recorded data were then used to generate a duplicated EM-1 signal at 2.3 GHz. The RPA output was injected into the front end of the Uchinoura station, in front of the low noise amplifier. The Uchinoura receiver successfully locked to the RPA signal and produced Doppler data as shown in Figure 5. Testing was done for several EM-1 modes of operation with different telemetry data rates from 72 ksps to 2 Msps. Uchinoura system also demonstrated it could track EM-1 signal with both the Costa loop (relying on telemetry symbols) and standard phase lock loop (relying on the residual carrier buried underneath the telemetry spectrum.)

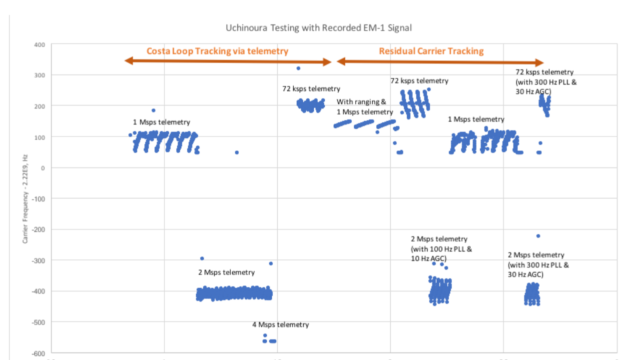

Figure 5. Uchinoura test with EM-1 signal, 2017-12-01

VI. MSU SUPPORT

The Morehead State University 21-m antenna system is being upgraded to support the Lunar Ice Cube mission, and other CubeSat launched on the EM-1 mission [4, 5]. This system will support deep space tracking at X-band (8.4 GHz). The system has some of DSN digital equipment that are specialized in telemetry, tracking and command in deep space environment. Due to limited budget and time constraint, the 21-m system does not have a full-scale test equipment that would simulate Lunar Ice Cube signal. The RPA helps filling this gap. It first recorded a test signal of Lunar Ice Cube characteristics that was generated by a more capable Test Signal Assembly in the DSN. The signal was later injected into the MSU system. Through this effort, the RPA helped verifying the ground system components and built up the confidence that the MSU ground system would be ready to support further interface testing with the Lunar IceCube flight system once it becomes available.

The recorded Lunar IceCube test signal comprises of a suppressed carrier modulated by telemetry data which are encoded with Turbo code, rate 1/6. The test objective is to demonstrate that the MSU ground system can demodulate the RPA emulated signal of Lunar IceCube and produce telemetry data after successful decoding. The preliminary test results demonstrated that the MSU equipment can successfully demodulate and decode the Lunar IceCube telemetry data at 64 ksps. Further testing is needed to demonstrate similar performance at 384 ksps where Lunar Ice Cube is expected to operate.

During the MSU testing, we were also able to characterize the performance of the RPA with and without the 10 MHz reference obtained from the on-site hydrogen maser clock. Figures 6 shows the measured frequency stability of the test signal, as detected by the receiver. With the 10 MHz reference input, the carrier signal was very stable. The frequency variation was within 20 mHz over short term and 70 mHz over 2.5 hrs. When relying on the internal clock, the carrier frequency drifted as much as 60 Hz just over 14 minutes, as shown in Figure 7. With such variation, while it is possible to track the carrier with a wide bandwidth, it would be difficult to maintain symbol demodulation with the maximum bandwidth allowed by the receiver. For the RPA to be able to support telemetry data testing, it needs to be synchronized to a stable external frequency reference.

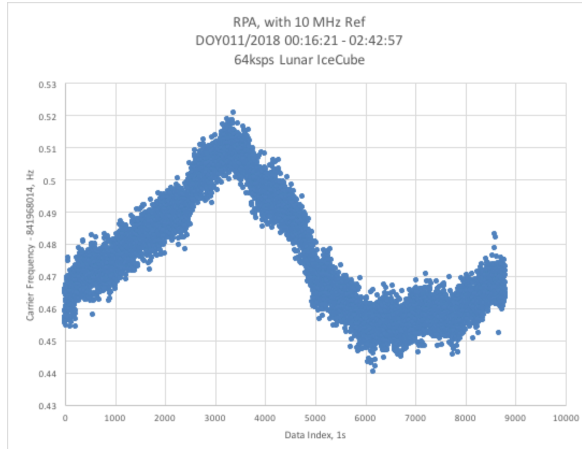

Figure 6. Stability of the test signal, with external reference.

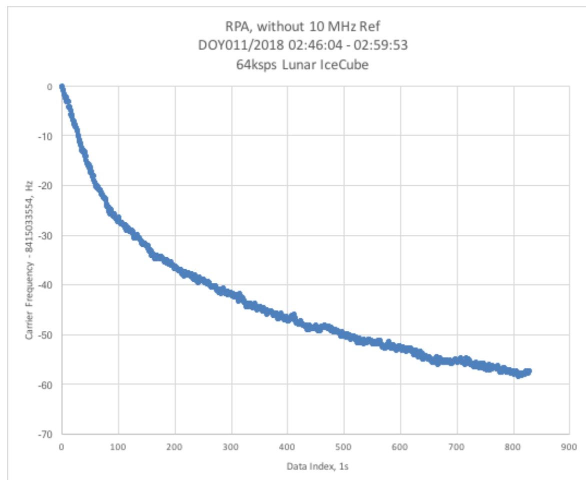

Figure 7. Stability of the test signal, with internal clock.

VII. CONCLUSION

In this paper we discussed the use of a commercial software defined radio in our testing effort at the Uchinoura and the Morehead State University ground stations. This test tool allows us to record, and later play back, the EM-1 signal generated by the spacecraft telecom subsystem and the emulated Lunar IceCube generated by the DSN Test Equipment. The test signal is of low cost, both in term of hardware procurement and software development, thanks to the available commercial products and public domain SDR software. One feature we most valued is the portability of the system. Its light weight makes it very easy to transport and conduct test at distant ground station, without a need for transportation shipment or on-site installation.

Both preliminary testing at Uchinoura and MSU have been successful. At Uchinoura, the ground station demonstrated it could track the recorded EM-1 signal. At the Morehead State University, the RPA enabled demonstration of functionality of the DSN-provided equipment there, where telemetry data emulating the Lunar IceCube mission was successfully demodulated and decoded. From our testing, we learned that it is critical to have the RPA using an external frequency reference – instead of relying on the internal clock - in order to achieve the necessary frequency stability needed for the test objectives.

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